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CAUSES OF SEA-LEVEL OSCILLATIONS

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Abstract: Excluding local vertical tectonic movements and migration of geoid undulations, sea-level changes imply variation in either the volume of sea water or capacity of the ocean basins.

Volume of ocean basins may be affected by changes either in area or mean depth from the geoid. With constant-radius tectonic models area is a minor variable, but with earth-expansion models, a major variable. Depths are affected by peneplanation (with transfer of sediment from land to sea) and by changes of geothermal gradient to expand or contract the relevant crustal column through paramorphic changes below.

Sea water volume may be affected by accretion of juvenile water from the deep interior, or by variation of the volume of water temporarily sequestered in terrestrial ice, atmosphere, or biosphere. The last two are comparatively trivial. Desiccation of sequestered seas has been suggested as a cause of sea-level rise. The Miocene evaporation of the Mediterranean could have caused a sea-level rise of some 10 m; and extensive salt deposits in the geological record could imply similar effects.

Icebergs, sea ice, and floating ice shelves are irrelevant because of Archimedes Principle. Even ice sheets resting on sediments below sea-level are supported by hydraulic uplift-pressure and are of little consequence. Only land ice is relevant, and isostatic adjustment of load transfer from depleted ocean to glaciated land scales down the sea-level effect by 40%.

Glaciation cycles have been favoured as the prime cause of eustatism. However the work of Vail and his co-authors has shown that the frequency and magnitude of oscillation persists through glacial and non-glacial periods alike. Hence a different major control must operate. Oscillations are skewed. Falls are rapid, rises very much slower. Increase of ocean capacity is the most likely cause of episodic falls. Release of juvenile water the most likely cause of secular rise.

Oscillations occur on time scales, from tens of millions of years through to single years. Palaeontological and radiometric dating through the Phanerozoic cannot differentiate more finely than a million years. Progressive refinement of the eustatic scale signature offers prospect ultimately of precise inter-continental correlations two or three orders better.

THE GEOID

The surface of the non-perturbed sea is the geoid. This equilibrium surface or mean sea-level is to a first order a sphere, at the second order an oblate ellipsoid, to a third order an oblate spheroid with north-south asymmetry. The fourth order introduces mid-latitude corrections. This may be expressed in gravity terms as:

$$\gamma = c_1 + c_2 \sin^2\phi + c_3 \cos^2\phi + c_4 \sin^2 2\phi + c_5 \sin(\lambda - c_6) \sin^2\phi$$

where ϕ is latitude measured positive in north and negative in south, c_1 is the mean gravity at the equator, c_2 the centrifugal acceleration at the equator, c_3 the north-south gravity asymmetry, and c_4 the mid-latitude correction. The equator has a crude ellipticity, with sea-level elevations around the Solomon Islands and mid-Atlantic more than 100 m higher than near Ceylon and the central Pacific. (Fig. 1). This ellipticity is expressed by the fifth term, where c_5 is the gravity difference between major and minor axes, c_6 is the longitude of a minor axis of ellipticity, and ϕ and λ are the latitude and longitude variables. Like the earth's gross tectonic features the 'meridians' of this ellipticity are significantly skewed north-side-westward. (Fig. 1). I suspect that these features migrate secularly westward on a humanly long but geologically short time-scale. But this has not been

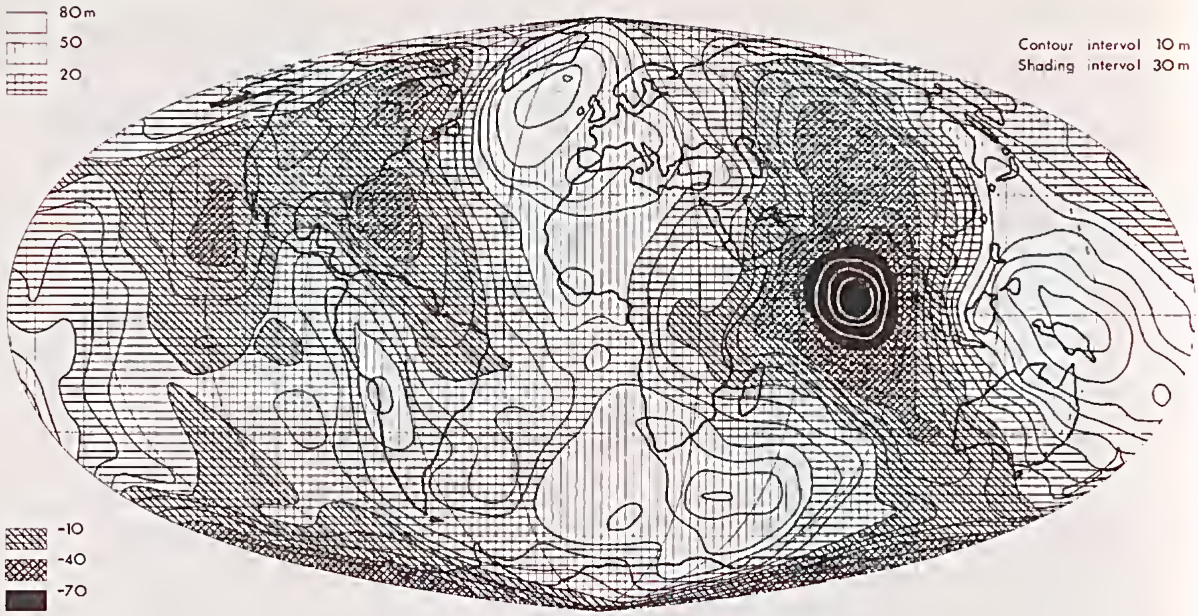

FIG. 1—The Geoid

tested. The geoid is still further modulated on smaller and smaller surfaces, in part permanent because of density heterogeneity in the lithophere, and in part transient support by existing stresses.

OSCILLATIONS ABOUT MEAN SEA-LEVEL

Oscillations due to the westward lag of tidal bulges of water and of lithosphere as the earth turns below the attracting moon and sun, and as the distance of these bodies vary with perigee and apogee and perihelion and aphelion, result in semi-diurnal, semi-lunar, and semi-annual tides. Water behaves as a liquid for all of these, while for the lithosphere only elastic yield is observed for times up to several months, some non-elastic yield is detectable for the annual and Chandler wobbles, largely non-elastic yield for the nutation (18.6 years) and wholly fluidal for the axial precession. As the moon, which at present has four times the tidal effect of the sun, was progressively closer in the past, tidal oscillation must have been much greater. Small short-period local changes are caused by migration of air pressure cells, by major storms, winds and sustained prevailing winds. Episodic seismic sea-waves with periods of some tens of minutes can cause rises of 100 m or more, and as they transport boats some kilometres inland, they could leave behind evidence of marine provenance in coastal sediments which have never been below sea-level. However such great waves only occur when the oceanic bathymetry (down to greatest depths) have salients to focus the wave on to the salient, and it is only along such shores that alertness for such cause is necessary.

TECTONIC MOVEMENTS

Migration of the geoidal rises and depressions described above (if real) may cause systematic regional oscillations of sea-level. In addition elevation or depression of individual regions relative to the geoid may be due to change of load on the lithosphere or change of temperature gradient.

Reduction of load may be due to erosion, melting of glaciers, change from humid to arid conditions, and evaporation of a sequestered lake or sea. Increase of load may be due to sedimentation or volcanic flows, or to loading due to lateral spreading from rising orogenic belts. Increase in geothermal gradient causes volume changes hence rise of lithosphere surface without change in load. At moderate depths the volume change is due to thermal expansion. At greater depths extending far into the mantle and even to the core, expansion is due to paramorphic phase changes. Phase changes to denser or less dense crystal lattices are governed by temperature and pressure. Increase of temperatures under constant overburden leads to expansion, which can be substantial.

Departures (indicated by gravity anomalies) may be induced and sustained by near-horizontal pressures or tensions, but not for times geologically long, because all such forces relax exponentially with time. Departures may also be sustained in dynamic equilibrium. When the plug is pulled from a full bath and water starts to drain, the statically level surface is depressed over the outlet (eventually to deepen to a vortex); the volume of the depression is such that the weight of water missing is equal to the sum of the vertical components of the viscous drag in the water. Similarly if convection really occurs below the lithosphere, a surface depression would be sustained dynamically above the downward flow, and a surface rise above upward limbs.

CAPACITY OF OCEAN BASINS

The total capacity of the ocean basins below the geoid may be affected by changes either in area or mean depths below the geoid. With earth-models which assume constant earth radius, the total area is a minor variable, because old oceanic floor is assumed to be removed by subduction *pari passu*, with creation of new crusts at mid ocean ridges, but with earth models assuming earth expansion, the area is a major variable, as almost all existing ocean floors have grown since the Palaeozoic, which (without subduction) means gross increase in area.

Depths of oceans are affected by (a) peneplanation of the lands with transfer of denudation products to the sea, (b) change of geothermal gradient, leading to paramorphic phase changes in the lithosphere and mantle. New crust at spreading ridges is 2 km deep or less. Young ocean basins are only 2 or 3 km deep, but as the lithosphere below them cools the moho boundary rises as 6 to 7 km-per-second material suffers paramorphic recrystallization to 8 km-per-second material, and the depth of the basin deepens through 4 km to nearly 5 km in old basins, (c) continental spreading as isostatic equilibrium moves slowly towards hydrostatic equilibrium. The relaxation time for isostatic disequilibrium of continental dimensions is of the order of one thousand years, whereas the relaxation time of departures from hydrostatic equilibrium is of the order of one thousand million years. To attain hydrostatic equilibrium all continents would have to spread to form an entire layer over the whole earth. As Lester King pointed out Pangaea when reassembled has a gross lensoid shape attributable to this process, indicating detectable hydrostatic spreading of continents on a time scale of 10^9 years, but none significant in 10^8 years.

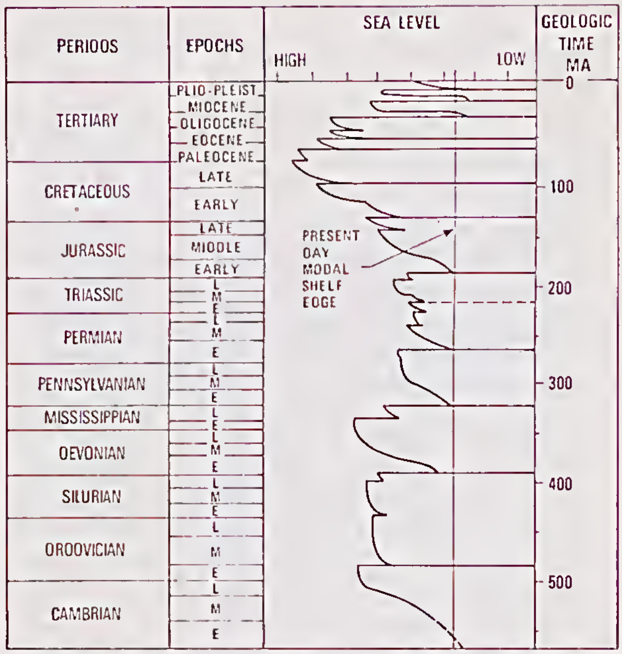

FIG. 2—Global super cycles of sea-level. (From Vail & Mitchum 1977)

VOLUME OF SEAWATER

The total volume of seawater may be affected by (a) accretion of juvenile water from the deep interior, (b) variation of the column of seawater temporarily sequestered in terrestrial ice, the atmosphere, biosphere, or in the hydration of rocks, or (c) loss from the planet.

So far as the planet as a whole is concerned it becomes a matter of the hydrogen budget. We continually gain protons from the solar wind, and we also lose excited hydrogen to space. The relative balance is not currently known, and could have been different in the past. The total water and the variation of water held in the atmosphere and biosphere are both trivial, and could not account for any significant sea-level change. Sub-aerial weathering of rock such as basalt involves the hydration of every ion present, with considerable change of volume. Submarine weathering is volumetrically insignificant, water volume loss more or less balancing rock volume increase. Total return to the sea of all water in hydrated minerals on land would raise the sea-level by a few decimetres, but changes of sea-level due to variation to terrestrial hydration can only be trivial.

Total evaporation of a sequestered sea could be significant. For example, Donovan & Jones (1979) estimated that the Miocene evaporation of the Mediterranean Sea could have raised the general level of the oceans by 12 m. As extensive salt deposits are known from various geological formations, desiccation could have been a cause of sea-level fluctuations of this order. If the earth radius was less during those earlier evaporation periods, the change of sea-level could have been substantially greater.

Concerning glaciation, icebergs, sea ice and floating ice shelves are irrelevant because the mass of water displaced equals the mass of the ice, so melting produces no change of sea-level. Even ice-sheets resting on sediments below sea-level can be largely omitted, because they are supported by the hydraulic uplift pressure of the groundwater seepage below them. Only land ice is relevant, but even here the effect on sea-level is only about one-third of that of the addition to the oceans of the volume of water from melted land ice, because the weight of this ice is transferred from the continent to lithosphere under the oceans. In relation to a reference continent, the ocean floor generally depresses under its increased water load, and the deglaciated continent rises owing to its loss of ice load.

A NEW ERA FOR EUSTATISM

From time to time a new concept or new technology triggers a rapid advance in a field of science which then gradually settles down again to a more normal slow growth. Eustatism has experienced such a leap forward during the last decade. Capability to discover and produce oil and gas at sea led to vast investment by all major oil companies, and every shelf and slope in the world has been probed by magnetometer, seismic reflection, and calibrating drills. Rapid development in seismic instrumentation and analysis has opened a cornucopia of new information about offshore sediments around the world stretching back far into the Mesozoic. The recent special volume of the American Association of Petroleum Geologists edited by Vail and Mitchum (1977) on seismic stratigraphy and global sea-level changes has opened a new era in eustatic studies.

Individual seismic reflectors (dated by drill-cores) are traced from marine deposits into coastal deposits and finally to the point of onlap against older sequences. Vail and his co-authors, using coastal onlap, toplap, and other stratigraphic criteria, recognize cycles of relative rise, stillstand, and fall of sea-level. They correlated these cycles within a region, and, comparing results from several continents, found that most of the regional cycles exist on a global scale. Anomalies in the curve for one region compared with the global curve identify local tectonic movements. This epochal work has placed several constraints on the causes of eustatic movements.

Hitherto, glacial cycles have been favoured as the prime cause of eustatism. Certainly the effect of waxing and waning of ice sheets is real. However the new work has established that the magnitude of oscillation of sea-level persists through glacial and non-glacial periods alike (Fig. 2). There are distinct frequencies of cycles. The super-cycles run for 10^8 years. Within those are major cycles of the order of 10^7 years, made up of shorter pulses of less than 10^6 years, which are clear in the drill cores but harder to identify and trace with present seismic technology. The global curves are empirical, with no pre-conceived cause. Quite clearly the principal cause of eustatic changes is not glacial.

Vail and his co-authors also found that the oscillations are markedly skewed. "One cycle of relative rise and fall of sea-level typically consists of a slow gradual relative rise, a period of still-stand and a rapid relative fall of sea-level. In detail the gradual rise consists of a number of smaller scale, rapid rises, separated by stillstands with no significant falls."

CAUSE OF EUSTATIC CYCLES

What then is the cause of sea-level cycles, and of their skewed form? The literature generally has not given a satisfactory answer. Indeed Donovan & Jones (1979) go so far as to doubt the new data, because they cannot see a mechanism! I discussed this question in my book on the expanding earth, before the publication of the new data (Carey 1976):

"The keynote of William Rubey's masterly presidential address to the Geological Society of America (Rubey 1951) was that the whole of the waters of the oceans had been exhaled from the interior of the earth, not as a primordial process, but slowly, progressively, continuously, throughout geological time." . . .

"As the generation of the ocean floors depends fundamentally on the same process as the outgassing of juvenile water it would be expected that the volume of sea water and the capacity of the ocean basins both increased in a related way. But not necessarily in phase. Several variables are involved, some with feedbacks and time-delays. There should be times when the capacity of the ocean basins increased more rapidly than the total volume of sea water, and vice versa. The former would result in general emergence and regression of the sea from the lands, the latter a transgression of the seas over the lowlands. This could happen on the gross scale of the order of whole geological periods, on epoch scale, and on progressively smaller scales to as short as a few years." . . .

"Secular variation of the temperature gradient in the mantle is another factor in this equation. When isotherms rise under a continent or megacontinent like Pangaea the depths of all phase transitions, from more dense to less dense paramorphs, descends to greater depths, and the surface bulges like rising dough, and there is general regression. Likewise as the mantle below a new ocean basin slowly loses its excess heat so that the isotherms retreat inwards, the phase transitions ascend so the floor of the basin sinks to greater depths. This increases the capacity of the basin, resulting in regression."

Skewed cycles commonly express repeating episodic events followed by exponential decay or relaxation. The time scales suggest that the long super cycles of more than a hundred million years relate to a core-mantle process. I suspect that the relatively episodic process is the increase in area of the ocean basins. The peri-continental spreading ridges (mis-named midocean ridges) divide the earth's surface into growing blocks on the same scale as the earth's primary heterogeneity of core and mantle (a few thousand km), and imply a thermal relaxation time of a few hundred million years. As orogenesis in my view is a diapiric phenomenon like the spreading ridges, the super cycles correlate with the major orogenic cycles. The shorter cycles may be primarily thermal and within the lithosphere, as the paramorphic moho boundary migrates up and down within the oceanic lithosphere in response to changes in thermal gradient induced by pulsed vulcanism.

A GLOBAL EUSTATIC CHRONOLOGY

The global curves will certainly be refined to precision within the near future. Then packets of sediments will be able to be correlated with certainty between regions and between distant continents. Within these packets, current seismic correlation cannot focus more sharply than a few million years, about equal to the best fossil and radioactive correlations. However the two latter have this imprecision at the boundaries of the packets as well as within, whereas the seismic stratigraphic correlation recognizes the bounding surface quite precisely. Hence the prospect that the finer oscillations seen in bore cores may be correlated absolutely between continents, and confirmed by their running signature, just as Trendall has done so brilliantly over hundreds of kilometres with the microbands in the Pilbara banded-iron formations.

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